The relative impact of invasive Australian acacias, fire and season on the soil chemical status of a sand plain lowland fynbos community

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Measurements of soil pH, resistance, cation exchange capacity and six macro- and five micro-elemental concentrations were made over a 12-month period in disturbed (burnt and *Acacia saligna*-infested) and undisturbed habitats in a sand plain lowland fynbos community. Two null hypotheses were tested, namely that there were no differences in soil chemical properties between (i) disturbed and undisturbed habitats and (ii) different seasons. A Friedman test was used to identify significant differences in soil chemical properties between different (i) habitats against seasons and (ii) seasons against habitats. With respect to acacia infestation, the first null hypothesis was rejected ($P < 0.01$) for all measured soil chemical properties, apart from Na, available P, Fe and Cu. With respect to disturbance by fire, this null hypothesis was rejected ($P < 0.01$) only for soil pH, Ca, available P and Mn. The second null hypothesis was rejected ($P < 0.05$) for soil pH, K, Na, available P, Fe and Zn. The impact of acacia infestation on soil chemical status was considerably greater than that of fire or season. The approximate two-fold increase in soil elemental concentrations evident in acacia-infested fynbos may detrimentally affect the survival of indigenous species adapted to a nutrient-impoverished environment.

Grond-pH, weerstand, katioon-uitruilvermoë en die konsentrasies van ses makro- en vyf mikro-elemente is gemeet oor 'n tydperk van 12 maande in habitatte wat versteurd (deur brand en infestasie van *Acacia saligna*) en wat onversteur is, in 'n sandvlakte laagland-fynbosgemeenskap. Twee nul-hipoteses is getoets, naamlik dat daar geen verskille in grond chemiese eienskappe is tussen (i) versteurde en onversteurde habitatte en (ii) tussen verskillende seisoene. Die Friedman-toets is gebruik om verskille in grond chemiese eienskappe te identifiseer tussen verskillende (i) habitatte teenoor seisoene en (ii) seisoene teenoor habitatte. Met betrekking tot infestasie deur acacia, is die eerste nul-hipotese verwerp ($P < 0.01$) ten opsigte van alle grond-chemiese eienskappe behalwe vir Na, beskikbare P, Fe en Cu. Met betrekking tot versteuring deur vuur, was hierdie nul-hipotese verwerp ($P < 0.01$) net vir grond-pH, Ca, beskikbare P en Mn. Die tweede nul-hipotese is verwerp ($P < 0.05$) ten opsigte van grond-pH, K, Na, beskikbare P, Fe en Zn. Infestasie deur acacia het dus 'n groter effek op grond-chemiese status uitgeoefen as óf vuur óf seisoen. Die ongeveer tweevoudige toename in grondelement-konsentrasies in fynbos wat deur acacia ingedring is mag 'n negatiewe uitwerking hê op die oorlewing van inheemse spesies wat aangepas is teenoor 'n omgewing met 'n gebrek aan voedingstowwe.

Keywords: Fire, fynbos, invasive alien acacias, season, soil chemistry

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Introduction

Lowland fynbos occurs along the coastal forelands which is a physiographic zone, within the biogeographical area Flora Capensis (Goldblatt 1978), situated between the mountains of the Cape Folded Belt and the coast (Moll *et al.* 1984). Lowland fynbos is divided (Moll *et al.* 1984) into sand plain lowland fynbos, associated with deep acidic sands of aeolian origin underlain by phyllites, of the west coast lowlands and limestone lowland fynbos which is restricted to calcareous, neutral to alkaline, shallow sands overlying limestone along the south coast (Schloms *et al.* 1983).

Sand plain lowland fynbos soils are characterized by having some of the lowest nutrient levels in world heathlands (Low 1983). Total N (Stock & Lewis 1986a) and total P (Mitchell *et al.* 1984; Brown & Mitchell 1986) concentrations and their various fractions vary seasonally and with soil depth. Increases in available P (Brown & Mitchell 1986), total N and exchangeable NH_4^+-N (Stock & Lewis 1986a) concentrations are evident at the soil surface immediately after fire, but these elevated levels are of short duration. Apart from these studies and soil macro-elemental data provided by Low (1983) and Lambrechts & Fry (1988) for various soil forms in sand plain lowland fynbos, there is relatively little information on the pre- and post-fire status of and seasonal variation in other soil elemental concentrations in this vegetation.

The potential nutrient enrichment of fynbos soils by populations of invasive Australian acacias, which have already replaced or infested much of the lowland vegetation (Hall 1979; Boucher 1981), is of concern for survival of indigenous sclerophyllous species adapted to a nutrient-impoverished environment. Annual dry litter-fall mass under acacias (Milton 1981) is about eight to ten times greater than in sand plain lowland fynbos (Mitchell *et al.* 1986), acacia foliar litter elemental concentrations (Ashton 1975; Milton 1981) are approximately four times greater and litter decomposition turnover times (Milton 1981) approximately half those of sand plain lowland fynbos litter (Mitchell *et al.* 1986; Mitchell & Coley 1987). Consequently, there is good reason to expect a considerable nutrient enrichment by acacias of sand plain lowland fynbos soils. However, little is known of the magnitude of this enrichment and how it compares with that exerted by natural phenomena such as fire and seasonal climatic variation. In this study, the relative impact of acacia infestation, fire and season on the soil chemical status of sand plain lowland fynbos are assessed.

Study area

Studies were carried out at the Fynbos Biome Project intensive study site at Pella (Jarman & Mustart 1988). Climate is typically mediterranean with a mean annual rainfall of about 590 mm falling predominantly in winter (Fuggle 1981; Jarman & Mustart 1988). The vegetation comprises a mosaic of different plant communities with different post-fire ages (Brownlie & Mustart 1988; Boucher & Shepherd 1988). Soils are about 2 m deep, well-drained, medium acidic, aeolian sands (Lambrechts & Fry 1988) of low P (Mitchell *et al.* 1984; Brown & Mitchell 1986) and N (Stock & Lewis 1986a) content.

The study area was confined to the north-western corner of the Pella site. It comprised an even-aged *Leucospermum parile – Thamnochortus punctatus* Mid-High Open Shrubland Community (Boucher & Shepherd 1988), a portion of which was infested by an *Acacia saligna* (Labill.) Wendl stand about 1 600 m^2 in area (*ca.* 40 × 40 m). The estimated age of the natural vegetation, deduced from Proteaceae node counts and fire history records (Brownlie & Mustart 1988), and mean age of the acacia stand was 11 years. Lambrechts & Fry (1988) classify and map the soil in the study area as a Geelhout series of the Clovelly form (MacVicar *et al.* 1977). It comprises a shallow orthic A horizon over a yellow-brown apedal B horizon which is a non-calcareous dystrophic medium sand (MacVicar *et al.* 1977).

Methods

Sampling procedure

During November 1986, a wild-fire destroyed a portion of the natural vegetation in the study area. The fire margin was halted at a distance of about 20 m from the canopy edge of the *A. saligna* stand. Apart from a few isolated individuals, no *A. saligna* populations occurred in the burnt portion of the even-aged community within the study area. Three transects, each 20 × 10 m in dimension and subdivided into 800 numbered 0.5 × 0.5-m quadrats, were established in the following habitats in the study area: (i) in the centre of the *A. saligna* stand, (ii) in undisturbed natural vegetation at a distance of 30 m from the acacia canopy edge and 30 m from the burn margin and (iii) burnt vegetation at a distance of 30 m from the burn margin and 50 m from the acacia canopy edge. All three transects occurred on a uniform substrate and slope. Commencing in December 1986, soils were sampled during the first week of each month over a period of 12 months from each of the three transects. Using a table of computer-generated random numbers, ten soil samples (75 mm in diameter and 25 mm deep) were taken at random from the numbered quadrats in each transect after removal of the litter layer. In burnt vegetation, samples included ash and charcoal. A record was kept of those numbered quadrats from which soils were sampled to eliminate the possibility of sampling from the same positions at subsequent intervals. Soil samples taken from each habitat at each sampling interval were bulked, dried at 40°C to a constant mass, thoroughly mixed and sieved through a 2-mm mesh.

Soil analyses

The following chemical properties (means of three determinations) were analysed in each soil sample: soil pH on a direct-reading pH meter with a combination glass–calomel electrode in a soil/1 M KC1 (1:2.5) suspension (Bessinger 1988) and resistance (in ohms at 25°C) on a soil/water paste in a Standard American Soil Cup (Hesse 1971).

Exchangeable cations (Ca, Mg, K, Na) were leached with unbuffered 0.1 M $SrCl_2$ (Edmeades & Clinton 1981) and concentrations individually determined in the leachate by atomic absorption. Lanthanum at a concentration of 1 250 mg dm^{-3} was used as a background suppressant in the determination of Ca and Mg. S values were calculated as the sum of cations expressed as mmol (+) kg^{-1} [cmol (+) kg^{-1} × 10]. Exchangeable acidity/Al was determined in the original leachates by titration using 0.02 M NaOH and a pH electrode to an end point of pH 7.0. The Sr-saturated soils were displaced with 1M NH_4OAc and the Sr determined by atomic absorption. Cation exchange capacity (CEC) was determined by summation ($SrCl_2$ exchangeable cations – S value + exchangeable acidity in 0.1 M $SrCl_2$ leachate).

Total N was determined by the Kjeldahl method (Bremner 1965). Plant-available (soluble reactive) P (P citric) was extracted with a 1% citric acid in a soil/solution ratio of 1:10 at 80°C for 1 h (Hesse 1971). Available P concentrations in the filtrates were determined colorimetrically using the ammonium molybdate blue method with $SnCl_2$ as a reductant (Olsen 1967).

Micro-elements (Fe, Cu, Mn, Zn) were extracted with 0.02 mol dm^{-3} $(NH_4)_2EDTA$ in a soil/solution ratio of 1:3 (1:10 for Mn) at 20°C for 60 min (Beyers & Coetzer 1971). Boron as boric acid was extracted with 0.02 mol dm^{-3} $CaCl_2$ in a soil/solution ratio of 1:2 at boiling point for 15 min (Parker & Gardner 1981). Micro-elemental concentrations in the filtrates were determined by atomic absorption.

Statistical analysis

Two null hypotheses were tested, namely that there were no differences in soil chemical properties between (i) disturbed (acacia-infested and burnt) and undisturbed habitats and (ii) different seasons (summer: December to February, autumn: March to May, winter: June to August, spring: September to November). A Friedman test (a non-parametric equivalent of a two-way ANOVA) was used to identify significant differences in

Table 1 A statistical comparison of soil chemical properties (means of 12 replicates) between disturbed and undisturbed habitats in a sand plain lowland fynbos community

	Average soil elemental concentration mmol kg^{-1}				
	Disturbed vegetation		Undisturbed vegetation	Friedman test statistic X_{r^2}	Conover-Friedman test statistic T_2
Element	Acacia	Fire	Fynbos	$DF = 2$	$DF = 2, 22$
Macro-elements					
Ca	13.29a	7.05b	5.32c	15.17***	18.89***
Mg	4.44a	1.51b	1.19b	18.37***	39.44***
K	0.96a	0.52b	0.46b	16.62***	34.02***
Na	0.45a	0.44a	0.32a	2.17	1.46
Total N	46.82a	25.28b	25.88b	18.00***	33.00***
P (citric)	0.266a	0.299b	0.250a	18.67***	38.50***
Micro-elements					
Fe	0.730a	0.665a	0.663a	0.67	0.31
Mn	0.093a	0.071b	0.040c	17.17***	27.63***
B	0.019a	0.012b	0.010b	11.62**	16.24**
Zn	0.012a	0.007b	0.005b	12.17**	11.31**
Cu	0.005a	0.004a	0.003a	5.54	3.39
pH (KCl)	4.93a	4.96a	4.40b	13.87***	15.86***
Resistance ohms	2714a	4653b	6086b	11.17**	9.57***
CEC mmol kg^{-1}	19.12a	9.90b	7.97b	13.17**	13.37***

Significance level ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$
Values with any letter in common not significantly different at $P < 0.05$
DF = degrees of freedom

soil chemical properties between different (i) habitats against seasons (12 replicates: months) and (ii) seasons against habitats (9 replicates: 3 habitats × 3 months). Both the Friedman statistic (X_{r^2}) and the Conover-Friedman statistic (T_2) using an F approximation were computed. A multiple-comparisons test on all rank sums was conducted where the Friedman and Conover-Friedman statistic probabilities were less than 0.05 (Sachs 1982).

Results

Acacia infestation

With respect to acacia infestation, the first null hypothesis was rejected ($P < 0.01$) for all measured soil chemical properties, apart from Na, available P, Fe and Cu (Table 1). Average soil CEC, Ca, Mg, K, total N, Mn, B and Zn concentrations in this habitat were approximately double and average soil resistance approximately half those in undisturbed vegetation. Relative differences in soil elemental concentrations between these two habitats, however, varied with season (Figures 1 & 2).

Fire

With respect to disturbance by fire, the first null hypothesis was rejected ($P < 0.01$) only for soil pH, Ca, available P and Mn (Table 1). Average levels of these were all higher than those in undisturbed vegetation. Other soil chemical properties, apart from K concentrations, exhibited levels elevated above those in undisturbed vegetation only in the first 3 to 6 months after fire (Figures 1 & 2). In comparison with acacia-infested vegetation, average soil Ca and Mn concentrations were lower, average soil pH was similar and only average soil available P levels were higher (Table 1).

Season

The second null hypothesis was rejected ($P < 0.05$) for soil pH, K, Na, available P, Fe and Zn (Table 2). Average soil K and Na concentrations were lower during spring and winter respectively, average soil pH was higher during summer and average soil-available P, Fe and Zn concentrations were higher during winter than in other seasons (Table 2).

Discussion

Acacia infestation

The impact of acacia infestation on soil chemical status was considerably greater than that of fire or season. Apart from soil-available P levels which were highest in burnt vegetation and soil Na, Fe and Cu concentrations which were similar in disturbed and undisturbed habitats, all other soil elemental concentrations in acacia-infested vegetation were much higher than those in burnt vegetation and exhibited an approximate two-fold increase over those in undisturbed vegetation. The enhanced soil elemental status of acacia-infested fynbos conforms with the increase expected from a higher litterfall mass under acacias, higher foliar litter elemental concentrations and more rapid decomposition turnover time of acacia litter (Ashton 1975; Milton 1981) than in indigenous sclerophyllous vegetation (Mitchell *et al.* 1986; Mitchell & Coley 1987). The importance of acacia litter as a nutrient source to the soil can be illustrated from a comparison of the estimated potential annual elemental input to the soil by acacia and sand plain lowland fynbos litterfall, calculated from litterfall mass and litter elemental data presented in the literature

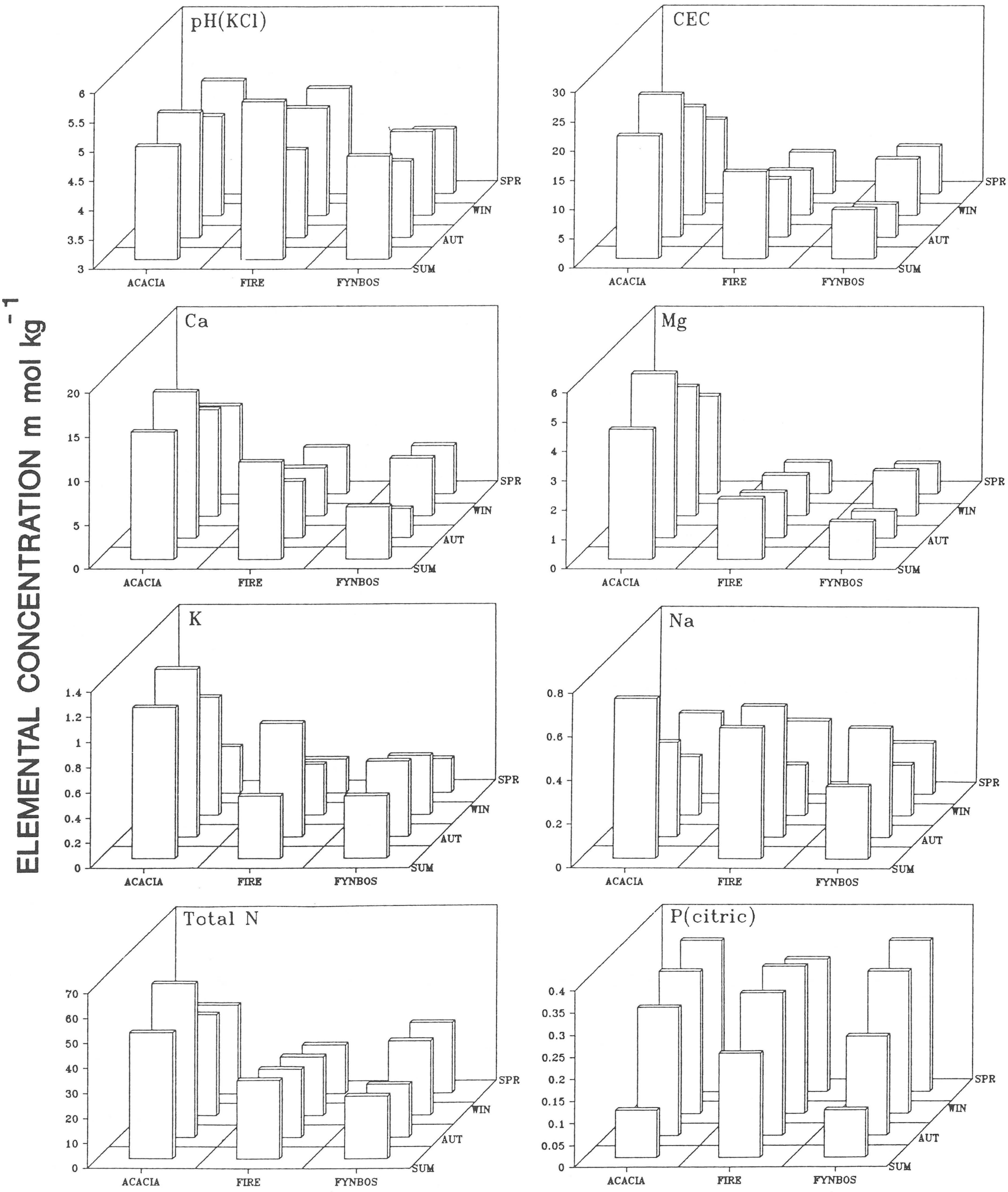

Figure 1 Seasonal variation in soil pH, cation exchange capacity (CEC) and macro-elemental concentrations in disturbed (acacia-infested and burnt) and undisturbed habitats of a sand plain lowland fynbos community.

(Ashton 1975; Milton 1981; Mitchell *et al.* 1986). The estimated potential annual elemental input to the soil by acacia and sand plain lowland fynbos litterfall respectively are 5.065 and 0.495 g Ca m^{-2} yr^{-1}, 1.938 and 0.064 g K m^{-2} yr^{-1}, 16.321 and 0.425 g N m^{-2} yr^{-1} and 0.442 and 0.019 g P m^{-2} yr^{-1}. A considerable potential nutrient enrichment of soils by acacias in fynbos is clearly apparent. Soil N has the greatest potential for enrichment by acacias. The estimated potential annual N input to the soil of 16.321 g N m^{-2} yr^{-1} by acacia litterfall exceeds not only the total N pool in the litter phytomass (0.566 g N m^{-2}), but also that in the above-ground phytomass (7.67 g N m^{-2}) of 11-year-old sand plain lowland fynbos (Low 1983). Annual N_2 fixation rates, integrated for season, reported for Australian acacia species (Lawrie 1981) that occur as invasive aliens in the south-western Cape suggest that the contribution of N, through N_2 fixation in acacia root nodules (Nakos 1977), to soil N status is small (0.0005 to 0.0746 g N_2 m^{-2} yr^{-1}) in comparison with that (0.112 g N m^{-2} yr^{-1}) contributed through atmospheric deposition (Stock & Lewis 1986b) and acacia litterfall. The importance of N_2 fixation to soil N status probably lies mainly in the production of a N-rich litter and subsequent N release through decomposition and mineralization of litter.

Based on macro-elemental status, soil in acacia-infested fynbos can be broadly classified as nutrient rich (mesotrophic) and moderately leached (Day 1983). Soil in this category usually supports vegetation with a sclerophyllous overstory and a seasonal herbaceous

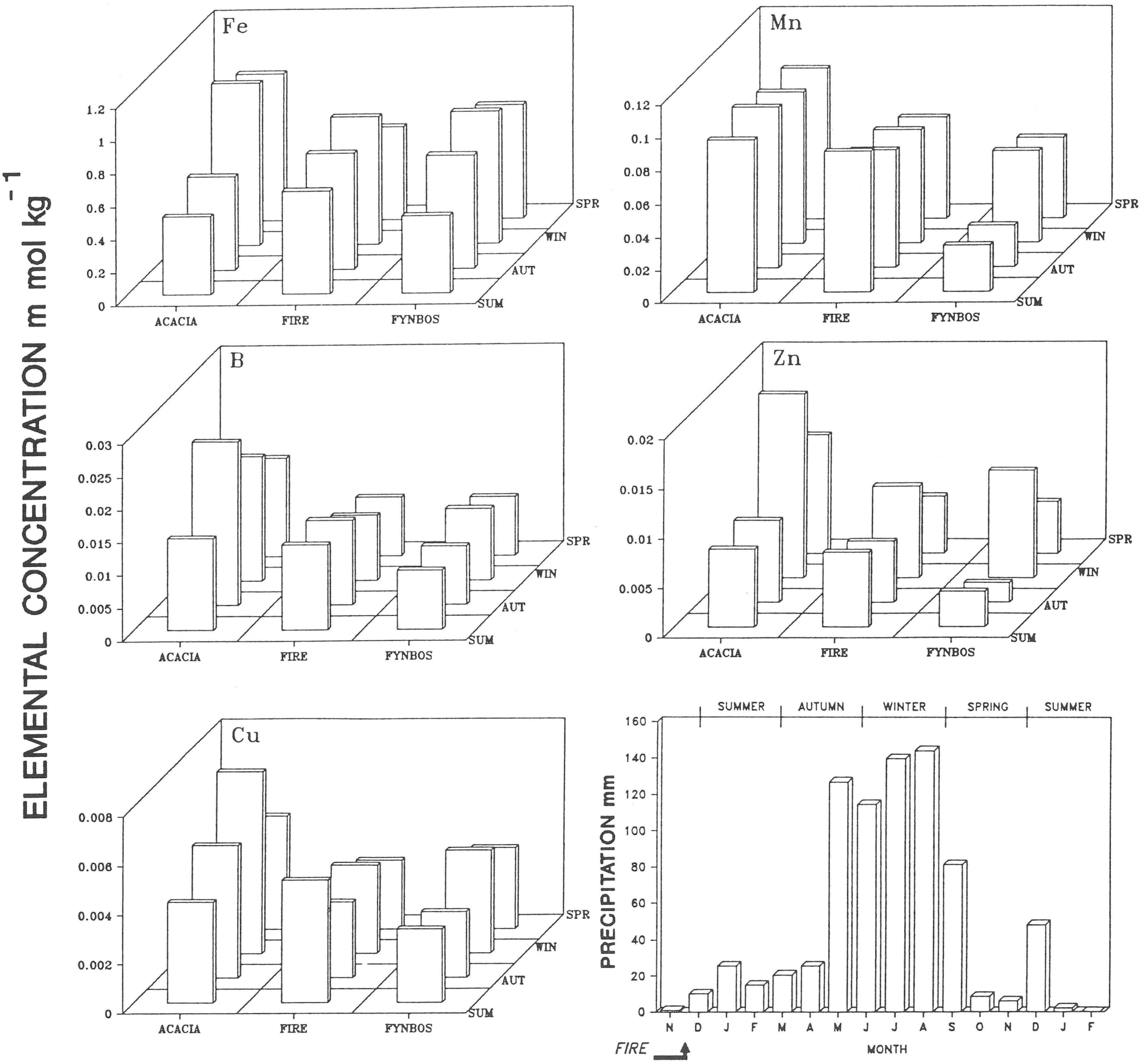

Figure 2 Seasonal variation in soil micro-elemental concentrations in disturbed (acacia-infested and burnt) and undisturbed habitats of a sand plain lowland fynbos community. Total monthly precipitation during period of study also shown (Source: Foundation for Research and Development, C.S.I.R., climatic records).

Table 2 A statistical comparison of soil chemical properties (means of 9 replicates) between different seasons in a sand plain lowland fynbos community

Element	Average soil elemental concentration mmol kg^{-1} Summer	Autumn	Winter	Spring	Friedman test statistic X_{r^2} $DF = 3$	Conover-Friedman test statistic T_2 $DF = 3, 24$
Macro-elements						
Ca	10.53a	8.78a	7.99a	6.91a	2.33	0.76
Mg	2.60a	2.68a	2.43a	1.81a	4.50	1.64
K	0.73a	0.94ab	0.60ac	0.30d	13.63**	9.19***
Na	0.56a	0.51a	0.24b	0.31b	14.77**	11.01***
Total N	35.62a	36.49a	31.02a	27.53a	3.00	1.00
P (citric)	0.151a	0.279b	0.326b	0.330c	19.17***	20.35***
Micro-elements						
Fe	0.525a	0.652b	0.854c	0.714ab	17.27***	14.19***
Mn	0.069a	0.065a	0.072a	0.067a	1.23	0.39
B	0.012a	0.016a	0.014a	0.011a	3.50	1.93
Zn	0.006a	0.005a	0.013b	0.008ac	11.90**	6.43**
Cu	0.004a	0.004a	0.005a	0.004a	4.83	1.77
pH (KCl)	5.13a	4.64b	4.66b	4.61b	7.43	3.35*
Resistance ohms	3205a	4367a	4432a	5933a	6.73	2.66
CEC mmol kg^{-1}	14.83a	13.28a	11.94a	9.26a	5.57	2.11

Significance level $***P < 0.001$, $**P < 0.01$, $*P < 0.05$
Values with any letter in common not significantly different at $P < 0.05$
DF = degrees of freedom

ground stratum (Specht & Moll 1983). This contrasts with the nutrient-poor (oligotrophic) and strongly leached soil of sand plain lowland fynbos which generally supports plant communities where both the overstory and understory are sclerophyllous (Specht & Moll 1983). The nutrient enrichment of soils by acacias could have a detrimental effect on the survival of indigenous sclerophyllous species adapted to a nutrient-impoverished environment. Experimental results of fertilizer additions to oligotrophic sclerophyll ecosystems show a reduced seedling survival rate among indigenous sclerophyllous species and an increased growth rate of well-established adult plants resulting in an accelerated life cycle and earlier death (Specht 1963; Heddle & Specht 1975). An increased growth rate probably also affects the water balance of the community and reduces the competitive ability of indigenous species with strong summer growth rhythms (Specht 1973; Grime 1979). The net result is the promotion of a more nutrient-demanding herbaceous component with a spring growth peak (Heddle & Specht 1975; Witkowski & Mitchell 1989). Milton (1981) suggested that the prevalence of grasses (indigenous and exotic) in areas cleared of acacias may provide supporting evidence for the change in soil nutrient status which acacias effect.

The similar average soil Fe and Cu concentrations evident in disturbed (acacia-infested and burnt) and undisturbed habitats is difficult to explain. Higher soil elemental concentrations were expected in acacia-infested and burnt vegetation as a consequence of soil enrichment by acacia litter and burnt residues respectively. Reduced solubilities of inorganic Fe (Lindsay 1979; Kabata-Pendias & Pendias 1984) and Cu ionic fractions (Lindsay 1972; McBride 1981) in the higher pH soils of acacia-infested and burnt vegetation may provide a possible explanation for the similar levels measured in disturbed and undisturbed habitats. The similar average soil-available P levels evident in acacia-infested and undisturbed vegegtation may be partly due to the high demand for P by Australian acacias (*ca.* 0.1260 g P m^{-2} yr^{-1} in an *Acacia holosericea* stand: Langkamp & Dalling 1982). Elevated soil-available P levels observed by Witkowski & Mitchell (1987) in *Acacia cyclops*-infested strandveld contrast with those of this study, but were probably due mainly to time of sampling (June to October). The largest differences in soil-available P levels between natural and acacia-infested vegetation could be expected during the winter–early spring period when increased soil moisture levels would be conducive to a high rate of mineralization of soil organic matter (Read & Mitchell 1983).

Fire

The impact of fire on the soil chemical status of sand plain lowland fynbos was smaller than that of acacia infestation and mainly a temporary feature. Soil-available P and pH in burnt vegetation exhibited levels elevated above those in undisturbed vegetation for 6 and 12 months after fire respectively (Figure 1). This compares favourably with Brown & Mitchell's (1986) observation that pre-fire soil-available (resin-extractable) P and pH levels in sand plain lowland fynbos were re-attained 4 and 7 months after fire respectively. Other soil elemental concentrations, excluding K, exhibited levels elevated above those in undisturbed vegetation only in the first 3 to 6 months after fire. Increased soil elemental levels observed in the immediate post-fire phase are in agreement with most other studies which have shown increases in soil total N (Mayland 1967; Christensen & Muller 1975; Stock & Lewis 1986a) and cation status (Debano & Conrad 1978; Rundel 1983) following fire, though some studies have shown no change or an actual decrease (Christensen 1973, 1977; Viro 1974; Debano & Conrad 1978). This lack of unanimity in experimental data has been attributed to differential fire characteristics arising from differences in the mass and spatial distribution of vegetation, degree of combustion and subsequent transport by wind or water of burnt residues (Raison 1979).

Season

The impact of season on the soil chemical status of sand plain lowland fynbos was small in comparison with that of acacia infestation and fire. Lower average soil K and Na concentrations evident during spring and winter respectively were attributed to leaching arising from higher precipitation levels during winter. Evidence of leaching was most clearly apparent in soils of acacia-infested fynbos where soil CEC, Ca, K, total N and B concentrations declined from autumn through to spring (Figures 1 & 2). Enhanced humification, microbial degradation and mineralization rates of organic matter under conditions of improved soil moisture (Billes *et al.* 1971; Read & Mitchell 1983; Tiwari *et al.* 1987) and higher atmospheric deposition rates of elements arising from increased precipitation levels during winter (Figure 2) may provide an explanation for the higher average soil-available P, Fe and Zn concentrations evident during this season. Phosphorus input from atmospheric deposition in sand plain lowland fynbos is strongly correlated with rainfall and occurs predominantly during winter (Brown *et al.* 1984). The input of 0.019 g P m^{-2} yr^{-1} from atmospheric deposition reported by Brown *et al.* (1984) is significant since it is similar to the estimated potential annual P input to the soil by sand plain lowland fynbos litterfall (*ca.* 0.019 g P m^{-2} yr^{-1}). With respect to Zn, it has been shown from studies of the Zn balance in surface soils of different ecosystems that the atmospheric input of this element always exceeds its output due to leaching and plant uptake (Kabata-Pendias & Pendias 1984), except in non-polluted forest regions of Sweden where the dispersal of Zn by water flux is higher than its atmospheric input (Tyler 1981). A proportionately greater atmospheric input relative to output of Zn under conditions of increased precipitation during winter could result in a greater accumulation of this element in the soil and explain the higher average soil Zn levels evident during this season.

Conclusions

The impact exerted by invasive Australian acacia infestations on soil chemical status of sand plain lowland fynbos is considerably greater than that of fire or seasonal climatic variation. The copious production of a nutrient-rich litter by acacias and its rapid decomposition relative to indigenous sclerophyllous vegetation is probably the principle factor responsible for the increased soil fertility levels evident in acacia-infested fynbos. Removal of invasive alien acacias by burning which also destroys the litter layer would have advantages over mechanical or chemical control measures which leave the litter layer intact, since the residual effect of decomposing acacia litter on soil nutrient status would be eliminated. To what extent enhanced soil elemental levels under acacias would persist following burning still needs to be assessed. Circumstantial evidence suggests that such enhanced levels would be transient. The dispersion of burnt residues by wind and water following fire and the observed rapid depletion through leaching of some elemental levels in the upper soil layers under conditions of increased precipitation during winter support this suggestion.

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